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Attorney's Docket No. 0021

**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

In re application of: Barten, Piet

Conf. No. 1890

Application No.: 10/553,301

Examiner: none assigned

Filed: August 1, 2006

Art Unit: 1638

For: Brassica Plants with High Levels of Anticarcinogenic Glucosinolates

**Commissioner for Patents**  
**P.O. Box 1450**  
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***Third-Party Submission-in-Published Application***  
***Under 37 CFR §1.99***

Requester submits herewith publications of which Requester is aware that Requester believes are material to the examination of Applicant's application.

This information disclosure statement is accompanied by Form PTO/SB/08 (substitute for Form PTO-1449) and legible copies of all non-patent literature listed in said form.

This submission is made within two months of the publication of the application by the United States Patent Office. The application was published on February 8, 2007, as publication no. 2007/0033675 A1.

However, the present US application was filed under 35 U.S.C. §371 from an international application having a filing date of April 13, 2004. The international application

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02 FC:1806

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*4/16/07*

received application no. PCT/NL04/00244. The international application was published on October 21, 2004, as publication no. WO/2004/089065 A1.

Although Applicant designated the United States in his international application, Applicant also designated 95 other countries. Applicant also did not comply with the requirements for entering the United States under 35 U.S.C §371 until August 1, 2006, almost two years after the international application was published, and Requester could not have known that Applicant had entered a national application in the United States until February 8, 2007, more than two years after the international publication date.

Within two months of the publication of the international application, Requester could not reasonably have anticipated that Applicant would enter the United States and therefore afford Requester the opportunity to make the present submission to the United States Patent Office at that time.

Requester respectfully requests that the Examiner consider the accompanying materials. The appropriate fee as set forth at 37 C.F.R. §1.17(i) for processing this request is provided.

The person making this request and submission is a practitioner who signs below on the basis of the information supplied to him.

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Pursuant to 37 C.F.R. §1.99(b)(1), enclosed is a check in the amount of \$310.00, providing the information disclosure fee as set forth in 37 C.F.R. §1.17(p), and the processing fee as set forth in 37 C.F.R. §1.17(i).

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Respectfully submitted,

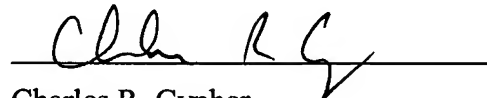
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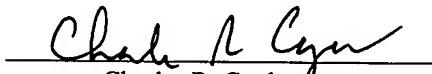
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I hereby certify that a copy of the foregoing with the enclosed references and Form PTO/SB/08 was served via first class mail on April 5, 2007, upon Applicant's counsel:

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<b>Substitute for form 1449A/PTO (MODIFIED)</b>  <b>INFORMATION DISCLOSURE STATEMENT BY APPLICANT</b>  (use as many sheets as necessary)				<b>Complete if Known</b>	
				Application Number	10/553,301
				Filing Date	August 1, 2006
				First Named Inventor	Barten, Piet
				Group Art Unit	1638 Confirmation no. 1890
				Examiner Name	None assigned at this time
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	C1	HANSEN, M., MOLLER, P. and SORENSEN, H.; Glucosinolates in Broccoli Stored Under Controlled Atmosphere; <i>J. Amer. Soc. Hort. Sci.</i> ; June 1995; Pages 1069-1074; Volume 120, Number 6; American Society for Horticultural Science; Alexandria, VA, United States				
	C2	KUSHAD, M., BROWN, A., KURILICH, A., JUVIK, J., KLEIN, B., WALLIG, M., JEFFERY, E.; Variation of Glucosinolates in Vegetable Crops of <i>Brassica oleracea</i> ; <i>J. Agric. Food Chem</i> ; 1999; Pages 1541-1548; Volume 47; American Chemical Society; Washington, DC, United States				
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## Glucosinolates in Broccoli Stored under Controlled Atmosphere

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**Additional index words.** *Brassica oleracea* L. var. *italica*, methylsulphinylalkylglucosinolates, indol-3-ylmethylglucosinolates, desulphoglucosinolates, low-oxygen atmosphere

**Abstract.** Content of total and individual glucosinolates were determined in, 'Marathon' broccoli florets (*Brassica oleracea* L. var. *italica*) stored 7 days at 10°C under air, 0.5% O<sub>2</sub>, 0.5% O<sub>2</sub> + 20% CO<sub>2</sub>, or 20% CO<sub>2</sub> atmosphere, followed by transfer to air for 2 days. 'Marathon' broccoli contained glucoraphanin, glucobrassicin, neoglucobrassicin, glucoiberin, 4-methoxyglucobrassicin, progoitrin, glucoalyssin, and gluconasturtiin. The methylsulfinylalkylglucosinolates (glucoiberin and glucoraphanin) and the indol-3-ylmethylglucosinolates (glucobrassicin, neoglucobrassicin and 4-methoxyglucobrassicin) accounted for 78% and 20% of the total content, respectively, in freshly harvested broccoli. CA treatment and storage time had no significant effect on the relative content of these two groups of glucosinolates. Freshly harvested broccoli contained 47 µmol glucosinolate/g dry weight. The total glucosinolate content increased 42% and 21% during 7 days storage under air and 0.5% O<sub>2</sub> + 20% CO<sub>2</sub>, respectively, as compared to freshly harvested broccoli, and decreased 15% in broccoli stored under 20% CO<sub>2</sub>. Treatment with 20% CO<sub>2</sub> in the absence of O<sub>2</sub> resulted in visible CO<sub>2</sub> injury and water soaking of the tissue. Aeration had no significant effect on total glucosinolate content but reduced the glucobrassicin content 35% in broccoli stored 7 days under 0.5% O<sub>2</sub> + 20% CO<sub>2</sub> or 20% CO<sub>2</sub> atmosphere. In contrast, the 4-methoxyglucobrassicin content increased during storage under low O<sub>2</sub> atmosphere and increased further after transfer to air.

Plants belonging to the order Capparales including Brassicaceae, are characterized by their content of glucosinolates (Bjerg and Sørensen, 1987a). Glucosinolates and their breakdown products are important aroma and flavor compounds in *Brassica* vegetables (MacLeod, 1976), such as cabbage, Brussels sprouts, broccoli, cauliflower, and horseradish. The most notable example is allyl isothiocyanate in mustard and horseradish arising from enzymic breakdown of sinigrin. This compound causes a pungent and lachrymatory response upon cutting and chewing (Gilbert and Nursten, 1972). Indol-3-ylmethylglucosinolates, which occur in appreciable amounts in several *Brassica* vegetables, are of interest for their potential contribution of anticarcinogenic compounds to the diet (Loft et al., 1992; McDanell et al., 1988).

Glucosinolates have a well defined structure with a side chain (R-group) and D- glucopyranose as β- thioglucoside attached to carbon atom no. 0 in (Z)-N-hydroximine sulfate esters (Table 1) (Olsen and Sørensen, 1981; Sørensen, 1990). The structural variation of the more than 100 glucosinolates isolated from various plant sources is mainly in the R-group (Fenwick and Heaney, 1983; Sørensen, 1990). This is also the case for glucosinolates identified as constituents of *Brassica* vegetables (Table 1).

Total and individual glucosinolate contents vary among cultivars and plant parts (Lewis and Fenwick, 198; Olsen and Sørensen, 1981;

Sang et al., 1984; Rahman et al., 1986; VanEtten et al., 1976), but the concentration is also affected by nutrient level and cultivation practice (Heaney et al., 1983; Josefsson, 1970). During the plants growth and development, glucosinolates are synthesized from amino acids in a series of steps (Ettlinger and Kjær, 1968; Kjær, 1960; Kjær and Larsen, 1980; Underhill and Kirkland, 1980), where many details are still unknown (Bjerg et al., 1987; Sørensen, 1991).

At present, only limited information is available relating to glucosinolate metabolism in *Brassica* vegetables after harvest. Chong and Bérard (1983) reported the variation in glucosinolate breakdown products in three cabbage cultivars during refrigerated storage. They found that the concentration of the thiocyanate ion, volatile isothiocyanates, and goitrin declined during storage and this was associated with decreasing quality of the cabbage. Similar results were observed in cabbage stored under controlled atmosphere (CA), except that the cabbage had more volatile isothiocyanates and goitrin during the early storage period and the content declined at a higher rate towards the end of storage (Bérard and Chong, 1985). Others (Hansen, 1979; Toivonen et al., 1982) found that white cabbage stored under CA increased in pungency, mustiness, and bitterness, but they did not study changes in glucosinolate content.

Broccoli is a commodity that benefits from storage under increased CO<sub>2</sub> and reduced O<sub>2</sub> concentrations (Lipton and Harris, 1974; Makhlof et al., 1989). Short term storage of broccoli under CA or in film wraps was found to extend shelf life and maintain quality by delaying yellowing and reducing loss of chlorophyll and ascorbic acid (Forney and Rij, 1991; Wang, 1979). It is not known to what extent increased CO<sub>2</sub> and reduced O<sub>2</sub> concentrations may affect glucosinolate content and thus flavor and nutritional quality of broccoli during storage. The objective of the present study was to determine the total and individual glucosinolates in broccoli stored under low O<sub>2</sub> and high CO<sub>2</sub> to understand better glucosinolate metabolism in *Brassica* vegetables after harvest.

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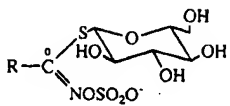
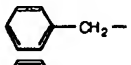
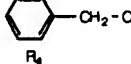
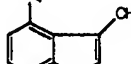
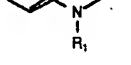
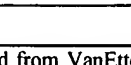
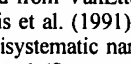
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Table 1. Numbers, structures and names of glucosinolates reported as constituents of *Brassica* vegetables<sup>1</sup>.

Glucosinolate skeleton				
				
No	Structure of R-groups	Semisystematic names of R-groups <sup>a</sup>	Trivial names	Brassica spp.
1	CH <sub>2</sub> =CH-CH <sub>2</sub> -	Allyl	Sinigrin	Cabbage, Brussels sprouts, cauliflower, broccoli
2	CH <sub>2</sub> =CH-CH <sub>2</sub> -CH <sub>2</sub> -	But-3-enyl	Gluconapin	Cabbage, Brussels sprouts, cauliflower, broccoli, Chinese cabbage
3	CH <sub>2</sub> =CH-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	Pent-4-enyl	Gluco brassicanapin	Cauliflower, broccoli, Chinese cabbage
4	CH <sub>2</sub> =CH-CH(OH)-CH <sub>2</sub> -	(2R)-2-Hydroxybut-3-enyl	Progoitrin	Cabbage, Brussels sprouts, cauliflower, broccoli, Chinese cabbage
7	CH <sub>3</sub> -S-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	3-Methylthiopropyl	Glucobervirin	Cabbage, cauliflower,
8	CH <sub>3</sub> -S-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	4-Methylthiobutyl	Glucorucin	Cabbage, Brussels sprouts, cauliflower, broccoli
10	CH <sub>3</sub> -SO-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	3-Methylsulphinylpropyl	Glucoberein	Cabbage, Brussels sprouts, cauliflower, broccoli
11	CH <sub>3</sub> -SO-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	4-Methylsulphinylbutyl	Glucoraphanin	Cabbage, Brussels sprouts, cauliflower, broccoli, Chinese cabbage
12	CH <sub>3</sub> -SO-CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	5-Methylsulphinylpentyl	Glucosulyssin	Chinese cabbage
15	CH <sub>3</sub> -SO <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -CH <sub>2</sub> -	4-Methylsulphonylbutyl	Glucocrysolin	Cabbage
16	 -CH <sub>2</sub> -	Benzyl	Glucotropaeolin	Cabbage
17	 -CH <sub>2</sub> -CH <sub>2</sub> -	Phenethyl	Gluconasturtin	Cabbage, Brussels sprouts, broccoli, Chinese cabbage
23	 -CH <sub>2</sub> - R <sub>1</sub> =H R <sub>4</sub> =H	Indol-3-ylmethyl	Glucobrassicin	Cabbage, Brussels sprouts, cauliflower, broccoli, Chinese cabbage
24	 -CH <sub>2</sub> - R <sub>1</sub> =OCH <sub>3</sub> R <sub>4</sub> =H	N-Methoxyindol-3-ylmethyl	Neoglucobrassicin	Cabbage, Brussels sprouts, cauliflower, broccoli, Chinese cabbage
26	 -CH <sub>2</sub> - R <sub>1</sub> =H R <sub>4</sub> =OH	4-Hydroxyindol-3-ylmethyl	4-Hydroxyglucobrassicin	Cabbage, Brussels sprouts, cauliflower, broccoli, Chinese cabbage
27	 -CH <sub>2</sub> - R <sub>1</sub> =H R <sub>4</sub> =OCH <sub>3</sub>	4-Methoxyindol-3-ylmethyl	4-Methoxyglucobrassicin	Cabbage, Brussels sprouts, cauliflower, broccoli, Chinese cabbage

<sup>1</sup>Compiled from VanEtten et al. (1976), Heaney and Fenwick (1980), Lewis and Fenwick (1987,1988), Sones et al. (1984), Goodrich et al. (1989), and Lewis et al. (1991).

<sup>a</sup>The semisystematic names of glucosinolates are composed of the name of the R-group followed by the word glucosinolate, e.g., allylglucosinolate for number-1 (Sorensen, 1990 and references cited therein).

## Materials and Methods

**Plant material.** 'Marathon' Broccoli heads (*Brassica oleracea* L. var. *italica*) were obtained on the day of harvest from Mann Packing Co., Salinas, Calif., top-iced and transported to the Mann Laboratory, Davis, Calif. where they were stored overnight at 0C. Miniflorets, 25 mm long and 20 to 70 mm in diameter, were excised from uniform heads of prime quality, surface sterilized in distilled water containing 100 ppm NaOCl for 5 min, drained, and divided on the basis of floret diameter into small (<40 mm), medium (40 to 50 mm) and large (>50 mm) sizes.

**Storage under CA.** Samples of broccoli (650 g) in a 1:2:1 (by weight) ratio of each floret size were placed in a 3.8-liter glass jar as one replicate, closed with a neoprene rubber stopper fitted with inlet and outlet polyethylene tubes. The jars were placed in a room at 10C for 7 days and ventilated with humidified gas at 10.1 ± 0.3 liters·h<sup>-1</sup>. The atmospheres were as follows: air, 0.5% O<sub>2</sub>, 0.5% O<sub>2</sub> + 20% CO<sub>2</sub>, or 20% CO<sub>2</sub> (all balanced with N<sub>2</sub>). After 7 days, the jars were transferred to air for 2 days at 10C. Oxygen and CO<sub>2</sub> concentrations were verified daily by analyzing 0.5 to 3 ml gas samples by electrochemical (model S-3AI; Applied Electrochemical, Sunnyvale, Calif.) and infrared analyzers (model PIR-2000; Horiba, Irvine, Calif.). The variation in O<sub>2</sub> and CO<sub>2</sub> concentrations was within ± 5%. After 2, 7, and 9 days of storage, two samples per treatment were removed for analysis except from the treatment with 20% CO<sub>2</sub> atmosphere. In

this treatment, samples were only removed at days 7 and 9.

**Freeze-drying.** Freshly harvested and stored broccoli florets (50 g) were frozen in liquid N<sub>2</sub> and kept in polyethylene bags at -40C until freeze-drying, usually within 1 month. Freeze-dried broccoli tissue was stored in sealed polyethylene bags at 4C until analysis.

**Extraction and isolation of glucosinolates.** Glucosinolates were extracted from freeze-dried, finely ground broccoli powder by the method of Bjerg et al. (1984). The samples (0.2 g) were spiked with a 100 µl internal standard solution containing 5.0 µmol·ml<sup>-1</sup> of sinigrin and glucobarbarin, and extracted three times with 5 ml boiling 70% methanol for 2 min using an Ultra-Turrax Homogenizer (Ika-Labortechnik, Staufen, Germany). The extract obtained after centrifugation was concentrated to dryness *in vacuo*, and the residue was dissolved in 2 ml deionized water. Desulfoglucosinolates were prepared and quantitatively determined by HPLC according to Bjerg and Sorensen (1987b) and Sorensen (1990). The glucosinolate concentration was calculated using glucobarbarin as internal standard.

**Statistical analysis.** Statistical significance was assessed for total and individual glucosinolates by one-way and two-way ANOVA for unbalanced data (SAS, Cary, N.C.). The sources of variation were treatment (air, 0.5% O<sub>2</sub>, 0.5% O<sub>2</sub> + 20% CO<sub>2</sub>, and 20% CO<sub>2</sub>) and time (0, 2, 7, and 9 days). Duncan's multiple range test and 95% confidence interval, respectively, were used to assess the location of the significant differences obtained.

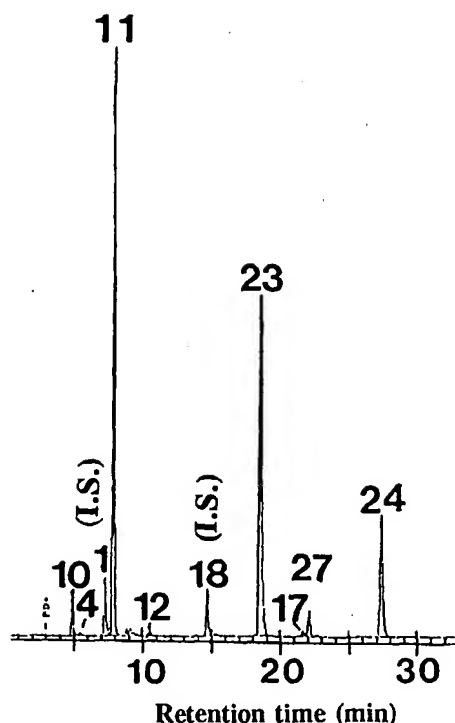


Fig. 1. Chromatogram of desulfoglucosinolates identified in freshly harvested 'Marathon' broccoli. The numbers refer to Table 1. No. 1 (sinigrin) and 18 (glucobarbarin) are internal standards (I.S.).

### Results and Discussion

**Total and individual glucosinolates.** HPLC separation of individual desulfoglucosinolates from freshly harvested 'Marathon' broccoli is shown in Fig. 1. The broccoli contained glucoraphanin (11), glucobrassicin (23), neoglucobrassicin (24), glucoiberin (10), 4-methoxyglucobrassicin (27), progoitrin (4), glucoalyssin (12), and gluconasturtiin (17). The major glucosinolates (found in concentrations  $>1 \mu\text{mol}\cdot\text{g}^{-1}$  dry weight) were glucoraphanin, glucobrassicin, glucoiberin, neoglucobrassicin, glucoiberin and 4-methoxyglucobrassicin. Others (Goodrich et al., 1989; Lewis et

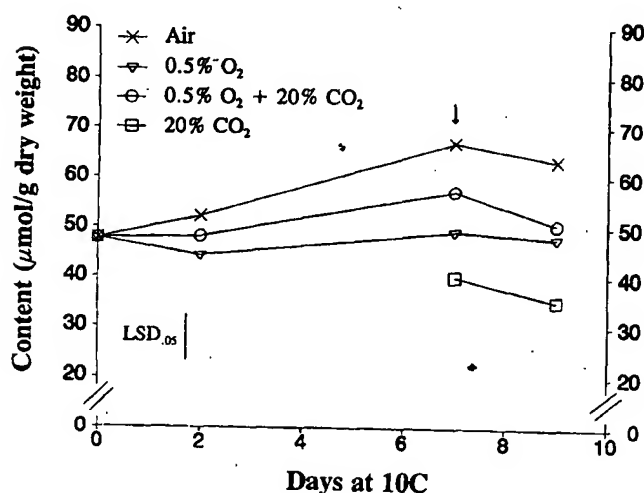
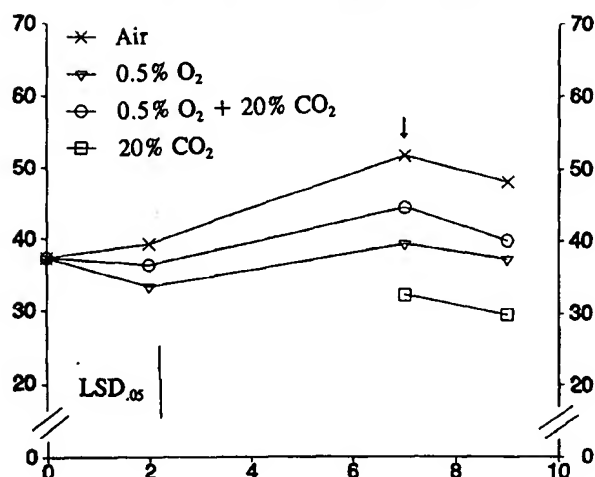
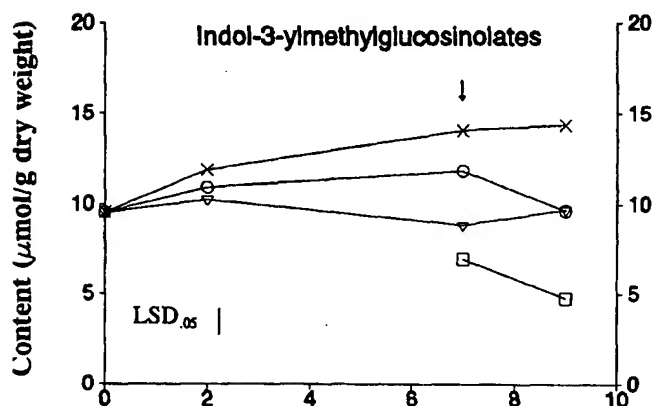


Fig. 2. Total glucosinolate content in broccoli stored 7 days under CA followed by 2 days aeration (↓ transfer to air). Data are means of two replicates.

### Methylsulphinylalkylglucosinolates



### Indol-3-ylmethylglucosinolates



### 4-Methoxyglucobrassicin

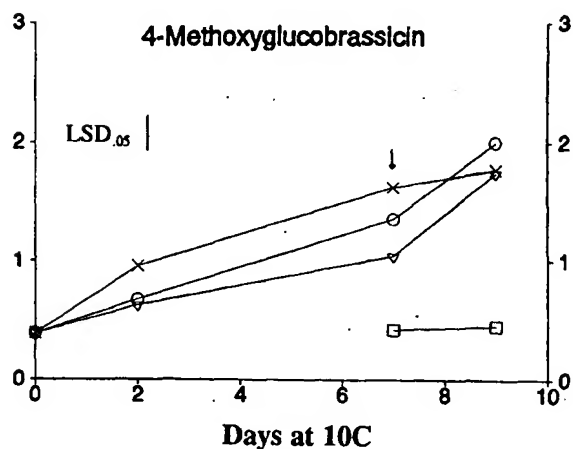


Fig. 3. Content of methylsulfinylalkylglucosinolates (glucoiberin and glucoraphanin), indol-3-ylmethylglucosinolates (glucobrassicin, neoglucobrassicin and 4-methoxyglucobrassicin) and 4-methoxyglucobrassicin in broccoli stored 7 days under CA followed by 2 days aeration (↓ transfer to air). Data are means of 2 replicates.

Table 2. Average concentration of major glucosinolates ( $\mu\text{mol}\cdot\text{g}^{-1}$  dry weight) in 'Marathon' broccoli stored 7 days under CA and transferred to air for 2 days. The relative content of the total is indicated in parentheses.

Glucosinolates <sup>a</sup>	Air	0.5% O <sub>2</sub>	0.5% O <sub>2</sub> + 20% CO <sub>2</sub>	20% CO <sub>2</sub>
Glucobrassicin	3.2 a <sup>b</sup> (5)	2.5 bc (5)	2.8 ab (5)	2.0 c (5)
Glucoraphanin	46.6 a (71)	35.8 bc (73)	39.2 ab (72)	29.0 c (76)
Glucobrassicin <sup>c</sup>	10.6 a (16)	6.2 c (13)	7.3 b (13)	4.5 d (12)
Neoglucobrassicin	1.9 a (3)	1.7 a (3)	1.8 a (3)	0.9 b (2)
4-Methoxyglucobrassicin <sup>c</sup>	1.7 a (3)	1.4 b (3)	1.7 a (3)	0.4 c (1)
Methylsulphinylalkylglucosinolates <sup>a</sup>	49.8 c (76)	38.3 bc (79)	42.0 ab (78)	31.0 c (82)
Indol-3-ylmethylglucosinolates <sup>c</sup>	14.2 a (22)	9.3 b (19)	10.7 b (20)	5.8 c (15)
Total glucosinolates	65.5 a (100)	49.0 b (100)	54.2 b (100)	37.9 c (100)

<sup>a</sup>Chemical structures are shown in Table 1.

<sup>b</sup>Numbers within a row followed by different letters are significantly different at  $P = 0.05$  by Duncan's multiple range test.

<sup>c</sup>Interaction between CA treatments and storage time.

<sup>a</sup>Methylsulphinylalkylglucosinolates: glucobrassicin and glucoraphanin.

<sup>c</sup>Indol-3-ylmethylglucosinolates: glucobrassicin, neoglucobrassicin and 4-methoxyglucobrassicin.

al., 1991) reported a similar glucosinolate profile in broccoli. Of the major glucosinolates, the methylsulfinylalkylglucosinolates (glucobrassicin and glucoraphanin) and the indol-3-ylmethylglucosinolates (glucobrassicin, neoglucobrassicin and 4-methoxyglucobrassicin) accounted for 78% and 20% of the total content, respectively, in freshly harvested broccoli.

**Storage under air.** Total glucosinolate content increased from  $47.1 \mu\text{mol}\cdot\text{g}^{-1}$  dry weight at day 0 to  $67.0 \mu\text{mol}\cdot\text{g}^{-1}$  dry weight at day 7 followed by a slight decline at day 9 as the broccoli deteriorated (Fig. 2). Incipient yellowing of florets was observed on day 7 and at day 9 the flower buds were moderate yellow (Hansen, 1993). Although the total glucosinolate content differed during air storage, none of the contents were significantly different from the others, probably due to too few observations. Chong and Bérard (1983) demonstrated that the concentration of glucosinolate products from cabbage increased during cold storage until the cabbage began to senesce, then the content rapidly declined. Analysis of variance for the content of individual glucosinolates indicated significant differences ( $P = 0.05$ ) for 4-methoxyglucobrassicin. The content increased from  $0.4 \mu\text{mol}\cdot\text{g}^{-1}$  dry weight at day 0 to  $1.8 \mu\text{mol}\cdot\text{g}^{-1}$  dry weight at day 9 in air stored broccoli.

**Storage under CA.** The green color of the florets was maintained under the three CA conditions used. The 20% CO<sub>2</sub> atmosphere resulted in severe off-odors. The total glucosinolate content increased 42% and 21% during 7 days storage under air and 0.5% O<sub>2</sub> + 20% CO<sub>2</sub>, respectively, as compared to freshly harvested broccoli (Fig. 2). This increase could have been associated with enhanced synthesis or a release of bound compounds during storage. Total glucosinolate content did not change for broccoli stored under 0.5% O<sub>2</sub>, but decreased 15% in broccoli stored under

20% CO<sub>2</sub> in the absence of O<sub>2</sub>. Exudation of cell sap, a symptom of physiological injury of the tissue, was visible in these latter samples. This symptom probably reflected membrane damage and cell rupture, conditions favorable for hydrolytic breakdown of glucosinolates by myrosinase catalyzed hydrolysis or autolysis (Olsen and Sorensen, 1981; Sorensen, 1990). In the intact cell, myrosinases are well separated from glucosinolates (Lüthy and Matile, 1984). When glucosinolates and myrosinases are brought in contact, a number of volatile and nonvolatile degradation products are formed depending on the structures of the glucosinolates and myrosinases and the actual conditions for hydrolysis (Sorensen, 1990; VanEtten and Tookey, 1983). During air and CA storage, the variation in the methylsulfinylalkylglucosinolate content (Fig. 3) was similar in both trend and magnitude to that of the total glucosinolates (Fig. 2). This result was in part due to the high relative content of methylsulfinylalkylglucosinolates (76% to 82%) in all samples (Table 2). The indol-3-ylmethylglucosinolate content (15% to 22% of total) increased 47% and 24% during 7 days storage under air and 0.5% O<sub>2</sub> + 20% CO<sub>2</sub> atmosphere, respectively, as compared to freshly harvested broccoli (Fig. 3). In contrast, the concentration did not change under 0.5% O<sub>2</sub> and decreased 28% following 7 days storage under 20% CO<sub>2</sub> (Fig. 3). No significant differences were found between the relative content of methylsulfinylalkyl- and indol-3-ylmethylglucosinolates with regard to CA treatment and storage period.

The average concentrations of total and individual glucosinolates for day 7 to 9 are shown in Table 2. Broccoli stored under air had the highest content of glucosinolates followed by that stored under 0.5% O<sub>2</sub> + 20% CO<sub>2</sub>, 0.5% O<sub>2</sub>, and 20% CO<sub>2</sub> (Table 2). There were

Table 3. Significance of CA treatments, storage time<sup>a</sup>, and interactions for content of total and individual glucosinolates, methylsulphinylalkylglucosinolates<sup>a</sup> and, indol-3-ylmethylglucosinolates<sup>a</sup>.

	Glucobrassicin	Glucoraphanin	Glucobrassicin	Neoglucobrassicin	4-Methoxyglucobrassicin	Methylsulphinylalkylglucosinolates	Indol-3-ylmethylglucosinolates	Total glucosinolates
CA-treatment	**	**	***	**	***	*	***	***
Storage time	NS	NS	**	NS	**	NS	NS	NS
Interaction	NS	NS	*	NS	*	NS	NS	NS

<sup>a</sup>Day 7 and 9.

<sup>a</sup>Methylsulphinylalkylglucosinolates: glucobrassicin and glucoraphanin.

<sup>a</sup>Indol-3-ylmethylglucosinolates: glucobrassicin, neoglucobrassicin and 4-methoxyglucobrassicin.

NS, \*, \*\*, \*\*\*Nonsignificant or significant at  $P = 0.01$ ,  $0.001$  and  $0.0001$ , respectively.



significant differences among CA-treatments in the content of total and individual glucosinolates for day 7 to 9 (Table 3).

When the broccoli stored under CA for 7 days was transferred to air for 2 days, there was not a significant decrease in total glucosinolate content (Table 3). Storage period (transfer to air from day 7 to 9) only affected glucobrassicin and 4-methoxyglucobrassicin contents. Aeration reduced the glucobrassicin contents 35% in broccoli stored 7 days under either 0.5% O<sub>2</sub> + 20% CO<sub>2</sub> or 20% CO<sub>2</sub>. Treatment with 0.5% O<sub>2</sub> + 20% CO<sub>2</sub> probably caused physiological stress in the tissue even though no symptoms of CO<sub>2</sub> injury were visible. This could result in an increase in the hydrolytic breakdown of glucosinolates upon aeration. On average, the glucobrassicin content decreased from 7.8  $\mu\text{mol}\cdot\text{g}^{-1}$  dry weight at day 7 to 6.5  $\mu\text{mol}\cdot\text{g}^{-1}$  dry weight at day 9. The opposite result was noted for 4-methoxyglucobrassicin (Fig. 3). The content increased during storage under low O<sub>2</sub> atmosphere and increased further after transfer to air. The average content of 4-methoxyglucobrassicin increased from 1.1  $\mu\text{mol}\cdot\text{g}^{-1}$  dry weight at day 7 to 1.5  $\mu\text{mol}\cdot\text{g}^{-1}$  dry weight at day 9. These results may indicate that storage could affect the nutritional value of broccoli since degradation products of indol-3-ylmethylglucosinolates, especially substituted indol-3-ylmethylglucosinolates, have been shown to have anticarcinogenic effects (Feldt et al., 1994 and references cited therein; Loft et al., 1992). In the present study, very low O<sub>2</sub> and very high CO<sub>2</sub> were imposed. Glucosinolate metabolism of broccoli stored at lower temperature and very extreme CA conditions should be investigated.

#### Literature Cited

- Berard, L.S. and C. Chong. 1985. Influence of storage on glucosinolate fluctuations in cabbage. *Acta Hort.* 157:203-210.
- Bjerg, B. and H. Sorensen. 1987a. Isolation of intact glucosinolates by column chromatography and determination of their purity, 59-75. In: J.P. Wathelot (ed.). *World crops: Production, utilization, description. Glucosinolates in rapeseeds: Analytical aspects.* Martinus Nijhoff Publ., Boston.
- Bjerg, B. and H. Sorensen. 1987b. Quantitative analysis of glucosinolates in oilseed rape based on HPLC of desulfoglucosinolates and HPLC of intact glucosinolates, p. 125-150. In: J.P. Wathelot (ed.). *World crops: Production, utilization, description. Glucosinolates in rapeseeds: Analytical aspects.* Martinus Nijhoff Publ., Boston.
- Bjerg, B., O. Olsen, K.W. Rasmussen, and H. Sorensen. 1984. New principles of ion-exchange techniques suitable to sample preparation and group separation of natural products prior to liquid chromatography. *J. Liquid Chromatography* 7:691-707.
- Bjerg, B., P.W. Kachlicki, L.M. Larsen, and H. Sorensen. 1987. Metabolism of glucosinolates. *Proc. 7th Intl. Rapeseed Congress, Poznan, Poland.* 2:496-506.
- Chong, C. and L.S. Bérard. 1983. Changes in glucosinolates during refrigerated storage of cabbage. *J. Amer. Soc. Hort. Sci.* 108:688-691.
- Ettlinger, M.G. and A. Kjaer. 1968. Sulfur compounds in plants, p. 58-144. In: T.J. Mabry, R.E. Alston, and V.C. Runeckels (eds.). *Recent advances in phytochemistry.* Appleton-Century-Crofts, New York.
- Fenwick, G.R. and R.K. Heaney. 1983. Glucosinolates and their breakdown products in cruciferous crops, foods and feeding stuffs. *Food Chem.* 11:249-271.
- Feldt, C., P. Moller, J. Otte, and H. Sorensen. 1994. Micellar electrokinetic capillary chromatography for determination of indolyl glucosinolates and transformation products thereof. *Ann. Biochem.* 217:62-69.
- Forney, C.F. and R.E. Rij. 1991. Temperature of broccoli florets at time of packaging influences package atmosphere and quality. *HortScience* 26:1301-1303.
- Gilbert, J. and H.E. Nursten. 1972. Volatile constituents of horseradish roots. *J. Sci. Food Agr.* 23:527-539.
- Goodrich, R.M., J.L. Anderson, and G.S. Stoewsand. 1989. Glucosinolate changes in blanched broccoli and Brussels sprouts. *J. Food Processing and Preserving* 13:275-280.
- Hansen, H. 1979. Organoleptic evaluation of white cabbage stored in commercial storage rooms at different level of CO<sub>2</sub>. *Acta Hort.* 93:29-44.
- Hansen, M. 1993. Volatile and non-volatile constituents and sensory quality of broccoli stored under low O<sub>2</sub> and high CO<sub>2</sub> atmosphere. PhD diss. The Royal Veterinary and Agr. Univ., Copenhagen.
- Heaney, R.K. and G.R. Fenwick. 1980. Glucosinolates in *Brassica* vegetables. Analysis of 22 varieties of Brussels sprout (*Brassica oleracea* var. *gemmifera*). *J. Sci. Food Agr.* 31:785-793.
- Heaney, R.K., E.A. Spinks, and G.R. Fenwick. 1983. The glucosinolate content of Brussels sprouts: Factors affecting their relative abundance. *Z. Pflanzenzüchtg.* 91:219-226.
- Josefsson, E. 1970. Glucosinolate content and amino acid composition of rapeseed (*Brassica napus*) meal as affected by sulphur and nitrogen nutrition. *J. Sci. Food Agr.* 21:98-103.
- Kjaer, A. 1960. Naturally derived isothiocyanates (mustard oil) and their parent glucosides, p. 122-176. In: W. Hetz, H. Grisebach, and G.W. Kirby (eds.). *Progress in the chemistry of organic natural products.* Springer-Verlag, New York.
- Kjaer, A. and P.O. Larsen. 1980. Non-protein amino acids, cyanogenic glucosides, and glucosinolates. Biosynthesis, specialist periodical report. *Chem. Soc. London* 6; 5(1977): 120-135; 4(1976):179-203; 2(1973):71-105.
- Lewis, J. and G.R. Fenwick. 1987. Glucosinolate content of *Brassica* vegetables: analysis of twenty-four cultivars of calabrese (green sprouting broccoli, *Brassica oleracea* L. var. *botrytis* subvar. *cymosa* Lam.). *Food Chem.* 25:259-268.
- Lewis, J. and G.R. Fenwick. 1988. Glucosinolate content of *Brassica* vegetables-Chinese cabbage pe-tsai (*Brassica pekinensis*) and pak-choi (*Brassica chinensis*). *J. Sci. Food Agr.* 45:379-386.
- Lewis, J.A., G.R. Fenwick, and A.R. Gray. 1991. Glucosinolates in *Brassica* vegetables: green-curd cauliflower (*Brassica oleracea* L. *Botrytis* group) and purple-headed broccoli (*B. oleracea* L. *Italica* group). *Lebensm.-Wiss. u.-Technol.* 24:361-363.
- Lipton, W.J. and C.M. Harris. 1974. Controlled atmosphere effects on the market quality of stored broccoli (*Brassica oleracea* L., *Italica* Group). *J. Amer. Soc. Hort. Sci.* 99:200-205.
- Loft, S., J. Otte, H.E. Poulsen, and H. Sorensen. 1992. Influence of intact and myrosinase-treated indolyl glucosinolates on the metabolism *in vivo* of metronidazole and antipyrine in the rat. *Food Chem. Toxicity* 30:927-935.
- Lüthy, B. and P. Matile. 1984. The mustard oil bomb: rectified analysis of the subcellular organisation of the myrosinase system. *Biochem. Physiol. Pflanzen* 179:5-12.
- MacLeod, A.J. 1976. Volatile flavour compounds of the cruciferae, p. 307-330. In: J.G. Vanghan, A.J. MacLeod, and B.M.G. Jones (eds.). *The biology and chemistry of the cruciferae.* Academic Press, New York.
- Makhlouf, J., F. Castaigne, J. Arul, C. Willemot, and A. Gosselin. 1989. Long-term storage of broccoli under controlled atmosphere. *HortScience* 24:637-639.
- McDanell, R., A.E.M. McLean, A.B. Hanley, R.K. Heaney, and G.R. Fenwick. 1988. Chemical and biological properties of indole glucosinolates (glucobrassicins): A review. *Food Chem. Toxicity* 26:59-70.
- Olsen, O. and H. Sorensen. 1981. Recent advances in the analysis of glucosinolates. *J. Amer. Oil Chem Soc.* 58:857-865.
- Rahman, M.H., O. Stolen, and H. Sorensen. 1986. Glucosinolate content in seed from siliques at different position of *Brassica campestris*. *Acta Agr. Scandinavia* 36:318-324.
- Sang, J.P., I.R. Minchinton, P.K. Johnstone, and R.J.W. Truscott. 1984. Glucosinolate profiles in the seed, root and leaf tissue of cabbage, mustard, rapeseed, radish, and swede. *Can. J. Plant Sci.* 64:77-93.
- Sones, K., R.K. Heaney, and G.R. Fenwick. 1984. Glucosinolates in *Brassica* vegetables. Analysis of twenty-seven cauliflower cultivars (*Brassica oleracea* L. var. *botrytis* subvar. *cauliflora* DC). *J. Sci. Food Agr.* 35:762-766.
- Sorensen, H. 1990. Glucosinolates: Structure-Properties-Function, p. 149-172. In: F. Shahidi (ed.). *Rapeseed/canola: Production, chemistry,*

- nutrition and processing technology. Van Nostrand Reinhold Publ., New York.
- Sorensen, H. 1991. Chemistry, VI:1931-1934. In: GCIRC—Congress, rapporteur evaluation. Summary of presentations in this section and review of recent years progress. GCIRC-Congr., Saskatoon, Can.
- Toivonen, P., J. Walsh, E.C. Lougheed, and D.P. Murr. 1982. Ethylene relationships in storage of some vegetables. In: D.G. Richardson and M. Meherivk (eds.). Controlled atmospheres for storage and transport of perishable agricultural commodities. Oregon State Univ., Symp. Ser. 1. Timber Press, Ore.
- Underhill, E.W. and D.F. Kirkland. 1980. Glucosinolates, p. 493-511. In: E.A. Bell and B.V. Charlwood (eds.). Secondary plant products: Encyclopedia of plant physiology. Springer-Verlag, New York.
- VanEtten, C.H. and H.L. Tookey. 1983. Glucosinolates, p. 15-30. In: M. Rechcigl (ed.). CRC handbook of naturally occurring food toxicants. CRC Press, Boca Raton, Fla.
- VanEtten, C.H., M.E. Daxenbichler, P.H. Williams, and W.F. Kwolek. 1976. Glucosinolates and derived products in cruciferous vegetables. Analysis of the edible part from twenty-two varieties of cabbage. *J. Agr. Food Chem.* 25:259-268.
- Wang, C.Y. 1979. Effect of short-term high CO<sub>2</sub> treatment on the marketing quality of stored broccoli. *J. Food Sci.* 44:1478-1482.

## Variation of Glucosinolates in Vegetable Crops of *Brassica oleracea*

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Glucosinolates were evaluated in 5 groups and 65 accessions of *Brassica oleracea* (50 broccoli, 4 Brussels sprouts, 6 cabbage, 3 cauliflower, and 2 kale) grown under uniform cultural conditions. Glucosinolates and their concentrations varied among the different groups and within each group. The predominant glucosinolates in broccoli were 4-methylsulfinylbutyl glucosinolate (glucoraphanin), 3-butenyl glucosinolate (gluconapin), and 3-indolylmethyl glucosinolate (glucobrassicin). Glucoraphanin concentration in broccoli ranged from 0.8  $\mu\text{mol g}^{-1}$  DW in EV6-1 to 21.7  $\mu\text{mol g}^{-1}$  DW in Brigadier. Concentrations of the other glucosinolates in broccoli varied similarly over a wide range. In Brussels sprouts, cabbage, cauliflower, and kale, the predominant glucosinolates were sinigrin (8.9, 7.8, 9.3, and 10.4  $\mu\text{mol g}^{-1}$  DW, respectively) and glucobrassicin (3.2, 0.9, 1.3, and 1.2  $\mu\text{mol g}^{-1}$  DW, respectively). Brussels sprouts also had significant amounts of gluconapin (6.9  $\mu\text{mol g}^{-1}$  DW). Wide variations in glucosinolate content among genotypes suggest differences in their health-promoting properties and the opportunity for enhancement of their levels through genetic manipulation.

**Keywords:** Glucosinolates; broccoli; *Brassica oleracea*; health; HPLC

### INTRODUCTION

Epidemiological data show that a diet rich in cruciferous vegetables, such as broccoli, cabbage, Brussels sprouts, cauliflower, and kale, can reduce the risk from a number of cancers and that the risk can be significantly reduced by an intake of as little as 10 g per day (Graham, 1983; Wattenberg, 1993; Kohlmeier and Su, 1997). The underlying mechanism(s) for the reduction of cancer by cruciferous vegetables is not clear. However, these vegetables are rich in sulfur-containing glucosides called glucosinolates. Glucosinolates are a class of more than 100 plant secondary metabolites present primarily in the crucifer family (Fenwick and Heaney, 1983). Glucosinolates exhibit minimal anticancer activity; however, upon cell damage they undergo hydrolysis by myrosinase (thioglucoside glucosylhydrolase, EC 3.2.3.1) to yield glucose, sulfate, and aglucones that can undergo fragmentation and/or molecular rearrangement yielding isothiocyanates, thiocyanates, oxazolidine-2-thiones, and nitriles, depending on the specific glucosinolate substrate, myrosinase isozyme, reaction pH, and presence of certain ions (Bones and Rossiter, 1996). A number of aglucone breakdown products have been reported to protect cells against cancer (Faulkner et al., 1998; Kohlmeier and Su, 1997; Tawfiq et al., 1995).

Several mechanisms have been proposed for cancer prevention by breakdown products of glucosinolates. There is substantial evidence linking ingestion of a glucosinolate rich diet with an increase in activity of phase II detoxification enzymes. Nijhoff et al. (1995)

reported that consumption of cooked Brussels sprouts reduced colorectal cancer and enhanced the synthesis of the detoxification enzyme glutathione *S*-transferase. In murine hepatic cells, glucosinolate breakdown products from cruciferous vegetables have been proposed to act as blocking agents against carcinogenesis by inducing quinone reductase activity (Tawfiq et al., 1995). The isothiocyanates, indole-3-carbinol (a product of glucobrassicin), phenylethylisothiocyanate (a product of gluconasturtiin), and sulforaphane (a product of glucoraphanin) have been shown to upregulate the synthesis of hepatic detoxification enzymes (Bradfield and Bjeldanes, 1984; Guo et al., 1992; Zhang et al., 1992) and protect against carcinogenesis (Morse et al., 1989; Wattenberg and Loub, 1978; Zhang et al., 1994). While most of the nitrile breakdown products have not been evaluated for their anticancer activity, a recent study demonstrated that the nitrile crambene (a product of progoitrin or epiprogoitrin) also upregulated the detoxification enzymes glutathione *S*-transferase and quinone reductase (Staack et al., 1998) and protects against aflatoxin-induced hepatocarcinogenesis in rats (Jeffery et al., 1996).

Comparative studies of glucosinolate distribution and variability between and within groups of the most widely consumed cruciferous vegetables such as broccoli, cabbage, cauliflower, Brussels sprouts, and kale are limited. To our knowledge, there are only two studies that have compared glucosinolate levels in the edible portions of more than three groups of these vegetables (Carlson et al., 1987b; Mullin and Sahasrabudhe, 1977). Even though one of these studies (Mullin and Sahasrabudhe, 1977) reports only total glucosinolates, the data suggest considerable differences in glucosinolate levels between and within the *Brassica* groups. In the more detailed study (Carlson et al., 1987a), 13 different glucosinolates have been reported in broccoli, Brussels sprouts, cauliflower, and kale. The authors reported that

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certain cultivars were highly correlated in their glucosinolate pattern and could be grouped together. Thus, broccoli with higher levels of glucoraphanin formed one group, Brussels sprouts and cauliflower with higher levels of glucobrassicin formed a second group, collard with higher levels of progoitrin formed a third group, and mustard green with higher levels of sinigrin formed a fourth group (Carlson et al., 1978a). However cabbage, an important *Brassica* vegetable, was not included in this study, and the glucosinolate comparisons were based on data collected over several years. This may confound the data, since in turnip, cabbage, and *Brassica napus* significant variations in glucosinolates are reported from year to year due to differences in climatic conditions (Carlson et al., 1987b; Fieldsend and Milford, 1994; Rosa et al., 1996).

Glucosinolate levels in *Brassica* are also affected by the growing location. Shelp and McLellan (1993) evaluated glucosinolate distribution in two broccoli cultivars grown at three different locations. They reported that differences in glucosinolate content among growing sites were greater than differences between cultivars. Factors that may have contributed to these differences included soil type, sulfate and nitrate fertilizer application, plant spacing, and date of harvest (Josefsson, 1970; Heany and Fenwick, 1980b; Griffiths et al., 1991; Rosa et al., 1996). Higher levels of glucosinolates were found in plants grown on clay soil than on sandy soil and in plants treated with sulfate than in plants treated with nitrate (Josefsson, 1970; Heaney and Fenwick, 1980b). In a study of *Brassica napus*, it was reported that higher nitrogen application increased the proportion of progoitrin at the expense of sinigrin (Zhao et al., 1994).

While previous studies on glucosinolate distribution in *Brassica* vegetables have indicated differences between and within groups, a significant portion of the variation may have resulted from variations in environmental and cultural factors. Therefore, the objective of this study was to compare glucosinolate levels in the edible portions of 66 genotypes from five *Brassica oleracea* groups including 50 var. *italica* (broccoli), 4 var. *gemmifera* (Brussels sprouts), 6 var. *capitata* (cabbage), 3 var. *botrytis* (cauliflower), and 2 *acephala* (kale) grown under uniform cultural practices in an attempt to identify differences due to genetic factors. Emphasis was placed on broccoli because of its economic importance and consumer preference.

## MATERIALS AND METHODS

**Materials.** Broccoli, Brussels sprouts, cabbage, cauliflower, and kale seeds were obtained from the Asgrow Seed Co. and Peto Seeds (Seminis vegetable seeds), the USDA Plant Genetics Resource Unit (Geneva, NY), and Dr. Mark Farnham of the USDA Vegetable Research Center (Charleston, SC). Lines included commercial hybrids, open-pollinated varieties, land races, inbreds, and doubled haploids developed by Farnham (1997) from commercial hybrids. In July 1996, seeds were germinated in Fafard growing mix no. 2 (Conrad Fafard, New Brunswick, Canada) in a greenhouse under natural day light. After 4 weeks in the greenhouse, seedlings were transplanted into a field plot of silty clay loam (Drumer) soil (pH 6.7) at the University of Illinois vegetable farm, in Champaign, IL. The field design was a randomized complete block (RCB) with three replicates of 15 plants each. Transplants of each entry were planted in single rows 75 cm apart and 40 cm in the row for a population equivalent of 33 333 plants per hectare. Water, fertilizer, and pesticides were applied according to standard cultural practices developed for cruciferous vegetables in Illinois (Foster and Maynard, 1998).

At optimum maturity, three uniform size plants free of insect and/or mechanical damage were selected from each replicate and the edible portions were cut, placed on ice, and immediately transported to the laboratory. Subsamples of 100 g from each plant per replicate were combined, weighed, frozen in liquid nitrogen, and lyophilized. Freeze-dried tissue was ground into a fine powder using a coffee mill and stored at  $-20^{\circ}\text{C}$  until further analysis.

**Glucosinolates Analysis.** Intact glucosinolates were analyzed according to Wathelet et al. (1991), with slight modification. A 0.2 g sample of freeze-dried powder from each replicate was placed in a capped 15 mL glass tube and heated on a heating block (Reacti-Therm III, Pierce, Rockford, IL) set at  $95^{\circ}\text{C}$  for 15 min. To each tube, 2 mL of boiling deionized water and 500  $\mu\text{L}$  of 1  $\mu\text{M}$  benzylglucosinolate (internal standard, Canola Council of Canada, Manitoba, Canada) were added. The tubes were heated for an additional 5 min, immediately cooled on ice, and centrifuged at 12000g for 10 min at  $4^{\circ}\text{C}$ , and the supernatant was saved on ice. The pellet was re-extracted with 1 mL of boiling water and centrifuged at 12000g for 10 min at  $4^{\circ}\text{C}$ , and the supernatant was collected, combined with the previously saved supernatant, and mixed. A 1 mL fraction of the supernatant was combined with 150  $\mu\text{L}$  of 0.5 M barium acetate, vortexed for 5 s, and layered on a DEAE Sephadex A-25 column. Glucosinolates were desulfated with arylsulfatase while on the column by adding 10 units of sulfatase suspended in 500  $\mu\text{L}$  of glass-distilled water to each column and capping it for 18 h. The desulfated glucosinolates were eluted from the column with 2 mL of water and separated on a Hitachi HPLC system (Hitachi Ltd., Tokyo, Japan) consisting of a variable UV detector set at 229 nm wavelength, a refrigerated autosampler, a column heater set at  $32^{\circ}\text{C}$ , and a Lichosphere RP-18 column (Merck, Darmstadt, Germany). Desulfoglucosinolates were eluted off the column in 46 min with a linear gradient of 0–20% acetonitrile in water at a flow rate of 0.8 mL/min. The type and amount of glucosinolates in each *Brassica* vegetable were calculated in comparison to certified glucosinolate levels in a standard rapeseed reference material (BCR 367, Commission of the European Community Bureau of References, Brussels, Belgium). Using benzylglucosinolate as an internal standard, the recovery of glucosinolates from the *Brassica* vegetables using this procedure was estimated at 95–97%. A representative chromatogram of the HPLC elution profile of glucosinolates from a broccoli sample is shown in Figure 1.

**Statistical Analysis.** Analysis of variance was performed on data between and within the groups. Mean separation was determined by least significant differences (LSD) at  $P = 0.05$  and standard error of the mean (SE). Mean separation was also determined for the effect of harvest date on glucosinolates in broccoli. Pearson's correlations of glucosinolates and vitamins evaluated in a companion study by Kurilich et al. (1998) were also determined.

## RESULTS AND DISCUSSION

**Variation in Glucosinolates among *Brassica oleracea* Groups.** Intact glucosinolates in broccoli, Brussel sprouts, cabbage, cauliflower, and kale were evaluated in order to determine variation in amounts and types across groups grown under similar conditions and using the same analytical procedure. A profile of 12 glucosinolates in *Brassica oleracea* groups is shown in Table 1. Data show significant differences in content of individual glucosinolate levels among the groups. In broccoli, the predominant glucosinolates were glucoraphanin (7.1  $\mu\text{mol g}^{-1}$  DW), glucobrassicin (1.1  $\mu\text{mol g}^{-1}$  DW), gluconapin (1.0  $\mu\text{mol g}^{-1}$  DW), and progoitrin (1.0  $\mu\text{mol g}^{-1}$  DW). Glucoraphanin and glucobrassicin concentrations in broccoli in this study were similar to those previously reported by Shelp et al. (1993) and Goodrich et al. (1989), but nearly 4-fold less than those reported by Hansen et al. (1995). Using gas chromatography,

Table 1. Mean Glucosinolate Content ( $\mu\text{mol g}^{-1}$  Dry Mass) in the Edible Tissues of *Brassica oleracea*<sup>a</sup>

glucosinolates		broccoli	Brussels sprouts	cabbage	cauliflower	kale
group	form					
aliphatics	sinigrin	0.1 $\pm$ 0.4	8.9 $\pm$ 0.2	7.8 $\pm$ 0.1	9.3 $\pm$ 0.1	10.4 $\pm$ 0.0
	gluconapin	1.0 $\pm$ 1.5	6.9 $\pm$ 0.7	0.7 $\pm$ 0.4	0.3 $\pm$ 0.2	1.0 $\pm$ 0.1
	glucobrassicinapin	0.3 $\pm$ 0.1	0.5 $\pm$ 0.1	0.2 $\pm$ 0.0	0.1 $\pm$ 0.0	0.1 $\pm$ 0.0
	progoitrin	1.0 $\pm$ 0.8	2.4 $\pm$ 0.4	0.2 $\pm$ 0.2	0.3 $\pm$ 0.1	0.6 $\pm$ 0.1
	epiprogoitrin	0.0 $\pm$ 0.1	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0
	napoleiferin	0.7 $\pm$ 0.6	0.4 $\pm$ 0.3	0.0 $\pm$ 0.1	0.2 $\pm$ 0.1	0.0 $\pm$ 0.0
	glucoiberin	0.1 $\pm$ 0.2	0.0 $\pm$ 0.1	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0
	glucoraphanin	7.1 $\pm$ 2.5	1.0 $\pm$ 1.3	0.1 $\pm$ 0.6	0.5 $\pm$ 0.3	1.0 $\pm$ 0.2
	glucoalysin	0.2 $\pm$ 0.1	0.1 $\pm$ 0.0	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0
	gluconasturtiin	0.4 $\pm$ 0.1	0.5 $\pm$ 0.1	0.3 $\pm$ 0.0	0.4 $\pm$ 0.0	0.4 $\pm$ 0.0
phenyl indoles	glucobrassicin	1.1 $\pm$ 0.4	3.2 $\pm$ 0.2	0.9 $\pm$ 0.1	1.3 $\pm$ 0.1	1.2 $\pm$ 0.0
	4-OH glucobrassicin	0.2 $\pm$ 0.1	0.6 $\pm$ 0.1	0.3 $\pm$ 0.0	1.6 $\pm$ 0.0	0.1 $\pm$ 0.0
	4-CH <sub>3</sub> OH glucobrassicin	0.4 $\pm$ 0.4	0.4 $\pm$ 0.2	0.3 $\pm$ 0.1	1.0 $\pm$ 0.1	0.2 $\pm$ 0.0
	neoglucobrassicin	0.2 $\pm$ 0.2	0.2 $\pm$ 0.1	0.2 $\pm$ 0.1	0.2 $\pm$ 0.0	0.1 $\pm$ 0.0
	total	12.8	25.1	10.9	15.1	15.0

<sup>a</sup> Values represent the mean  $\pm$  SEM. Means and SEM were calculated from the following accessions: broccoli, 50; Brussels sprouts, 4; cabbage, 6; cauliflower, 3; kale, 2.

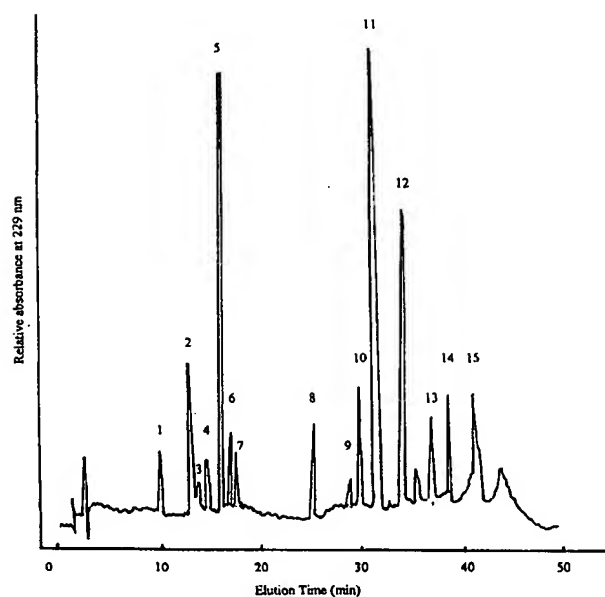


Figure 1. Typical HPLC chromatogram of desulfoglucosinolates in broccoli. Peaks: 1, glucoiberin; 2, progoitrin; 3, epiprogoitrin; 4, sinigrin; 5, glucoraphanin; 6, napoleiferin; 7, glucoalysin; 8, gluconapin; 9, 4-hydroxy-glucobrassicin; 10, glucobrassicinapin; 11, benzylglucosinolate (internal standard); 12, glucobrassicin; 13, gluconasturtiin; 14, 4-methoxy-glucobrassicin; 15, neoglucobrassicin.

Carlson et al. (1987b) found that in broccoli, the concentrations of glucoraphanin and glucobrassicin were similar. However, in the present study we found glucoraphanin concentration to be about 7-fold higher than that of glucobrassicin (Table 1). It is interesting to note that while estimation of glucoraphanin and glucobrassicin levels in the previous studies were made in mature flower heads, a more recent study (Fahey et al., 1997) reported a complete absence of glucobrassicin in broccoli seedlings. Similarly, we found 50% higher glucobrassicin in fully developed Packman broccoli heads (15–20 cm diameter) than in immature heads (5–10 cm diameter, data not shown). These results suggest that glucobrassicin synthesis is active during later stages of broccoli development. In Brussels sprouts, the predominant glucosinolates are sinigrin (8.9  $\mu\text{mol g}^{-1}$  DW), gluconapin (6.9  $\mu\text{mol g}^{-1}$  DW), glucobrassicin (3.2  $\mu\text{mol g}^{-1}$

DW), and progoitrin (2.4  $\mu\text{mol g}^{-1}$  DW). Our results are similar to those previously reported by Heaney and Fenwick (1980b) and Goodrich et al. (1989). In contrast, Carlson et al. (1987a) reported a higher level of glucobrassicin in Brussels sprouts than that reported in the present study and that the glucobrassicin concentration is nearly 40-fold higher than the sinigrin concentration. However, Carlson et al. (1987a) quantified glucobrassicin indirectly by measuring the amount of thiocyanate ion released by the action of myrosinase. This procedure appears to overestimate glucobrassicin concentration and does not differentiate between glucobrassicin and neoglucobrassicin (Heaney and Fenwick, 1980a). In a more recent study, Heaney and Fenwick (1993) compared several glucosinolate analysis procedures and suggested that high-pressure liquid chromatography is more reliable and less time-consuming than other methods.

In cabbage, the predominant glucosinolates were sinigrin (7.8  $\mu\text{mol g}^{-1}$  DW), glucobrassicin (0.9  $\mu\text{mol g}^{-1}$  DW), and gluconapin (0.7  $\mu\text{mol g}^{-1}$  DW). In agreement with our data, Pocock et al. (1987) found high levels of sinigrin and glucobrassicin compared to the other glucosinolates in English white cabbage. In addition, they found significant amounts of glucoiberin in the three cultivars tested. In a survey of 22 cabbage cultivars, VanEtten and Daxenbichler (1976) found higher levels (10–50%) of glucoiberin than either sinigrin or glucobrassicin. Rosa (1997) reported that glucoiberin concentration in cabbage is about 2-fold higher in the roots than in the leaves and it decreased in both tissues with an increase in plant age. In the present study, glucoiberin concentration was very low ( $\leq 0.06 \mu\text{mol g}^{-1}$  DW) in the six accessions tested. Both Pocock et al. (1987) and VanEtten and Daxenbichler (1976) used GC to detect glucoiberin, which suggests that GC may be more sensitive than HPLC for detecting this compound.

In cauliflower, the most abundant glucosinolates were sinigrin (9.3  $\mu\text{mol g}^{-1}$  DW), 4-hydroxy glucobrassicin (1.6  $\mu\text{mol g}^{-1}$  DW), and glucobrassicin (1.3  $\mu\text{mol g}^{-1}$  DW). Carlson et al. (1987b) and Sones et al. (1984) also found higher levels of sinigrin and glucobrassicin compared to other glucosinolates in cauliflower. However, the amounts that they reported are significantly less than those we report in this study. Both Carlson et al. (1987b) and Sones et al. (1984) used GC to estimate the level of glucosinolates. According to Sones et al. (1984), the GC

procedure underestimates the level of glucosinolates in cauliflower.

In kale, the most abundant glucosinolates were sinigrin ( $10.4 \mu\text{mol g}^{-1}$  DW), glucobrassicin ( $1.2 \mu\text{mol g}^{-1}$  DW), gluconapin ( $1.0 \mu\text{mol g}^{-1}$  DW), and glucoraphanin ( $1.0 \mu\text{mol g}^{-1}$  DW, Table 1). Similarly, Carlson et al. (1987a) and Rosa et al. (1996) reported higher sinigrin and glucobrassicin but only a trace amount of glucoraphanin in kale leaves. However, in flowering Chinese kale, up to 68% of the total glucosinolates were reported to be glucoraphanin (Hill et al., 1987). In this study, gluconasturtiin concentration in kale was similar to that in the other four vegetable groups (Table 2).

An important factor that may have contributed to the difference in glucosinolate content among the groups is the difference in tissue types tested. In this study, immature flowers were analyzed in broccoli and cauliflower, leaves in cabbage and kale, and axillary buds in Brussels sprouts. Variation in glucosinolate types and concentrations among plant parts was previously reported in turnip, cabbage, and *Brassica napus* (Booth and Walker, 1991; Carlson et al., 1987a; Clossais-Besnard and Larher, 1991; Rosa, 1997). In turnip, gluconapin and glucobrassicin were higher in the tops than in the roots, while glucoraphanin, progoitrin, glucoalysin, glucobrassicin, and total glucosinolates were higher in the roots than in the tops (Carlson et al., 1987a; Rosa et al., 1996). In cabbage, Rosa (1997) found higher indole glucosinolates in the roots and higher aliphatic glucosinolates in the leaves. Differences in glucosinolate levels between plant parts are not linked to mobilization between organs; instead they are believed to be synthesized and stored within each organ (Rosa et al., 1996; Clossais-Besnard and Larher, 1991).

**Variation in Glucosinolates within *Brassica oleracea* Groups.** Evaluation of glucosinolate levels showed significant differences between accessions within each group (Table 2). Among the broccoli accessions tested, the highest amount of glucoraphanin was found in Brigadier ( $21.7 \mu\text{mol g}^{-1}$  DW) followed by Wintergarden ( $17.5 \mu\text{mol g}^{-1}$  DW), and Majestic ( $16.0 \mu\text{mol g}^{-1}$  DW). The lowest amount of glucoraphanin ( $0.8 \mu\text{mol g}^{-1}$  DW) was found in EV6-1. Carlson et al. (1987b) also found differences in glucoraphanin among six broccoli accessions; however, the differences were relatively small (less than 3-fold) compared to differences reported in this study (more than 27-fold). In *Brassica napus* and *Brassica oleracea*, Rosa (1996) reported a significant effect of accessions on glucosinolate levels.

In some broccoli accessions (example Peto no. 3), the glucoraphanin level represents up to 90% of the aliphatic glucosinolates. The action of the hydrolyzing enzyme myrosinase on glucoraphanin causes the release of glucose and an unstable intermediate that rearranges irreversibly to form sulforaphane and/or sulforaphane nitrile. Basic pH and high temperature enhance sulforaphane formation, while acidic pH and ferrous ions enhance sulforaphane nitrile formation (Fenwick et al., 1983). Sulforaphane is the most potent naturally occurring inducer of phase II enzymes, including quinone reductase and glutathione *S*-transferases (Prochaska et al., 1992). Induction of phase II enzymes has been shown to protect cells against toxic electrophiles, including carcinogens such as 9,10-dimethyl-1,2-benzanthracene (Zhang et al., 1992, 1994). Sulforaphane nitrile, however, is inactive against hepatic glutathione concentration and glutathione-*S*-transferase activity

(Ringenberg and Wallig, 1996). In broccoli, the concentration of sulforaphane was reported to be between 1.9 and  $3.7 \text{ mg g}^{-1}$  DW and sulforaphane nitrile between 0.2 and  $0.3 \text{ mg g}^{-1}$  DW (Chiang et al., 1998).

Other aliphatic glucosinolates found in varying amounts in broccoli include epiprogoitrin, napoleiferin, glucoalysin, and gluconapin. The sum of these compounds is listed as residual aliphatics (Table 1). Differences in concentrations of these compounds among the broccoli accessions were relatively small, except in DeCicco, which showed significantly higher concentration of glucoalysin ( $16.0 \mu\text{mol g}^{-1}$  DW), and Peto no. 7, which showed significantly higher concentrations of progoitrin ( $7.9 \mu\text{mol g}^{-1}$  DW) and gluconapin ( $17.1 \mu\text{mol g}^{-1}$  DW). Differences in the profile of aliphatic glucosinolates among broccoli lines have been attributed to genetic variation (Giamoustaris and Mithen, 1996). Several loci have been identified that are involved in the partitioning of aliphatic glucosinolates. The *Gsl-elong* locus is responsible for the elongation of the carbon side chain (Mithen et al., 1995), while several other loci are affiliated with side chain rearrangements (Giamoustaris and Mithen, 1996; Magrath et al., 1994). Partitioning into the various forms has been proposed to be regulated by the presence of nonfunctional alleles at these loci (Giamoustaris and Mithen, 1996).

Broccoli accessions also showed significant differences in indole glucosinolates content. Glucobrassicin is the most abundant indole glucosinolate in broccoli, representing nearly 60% of the indoles and about 10% of the total glucosinolates (Table 2). The highest concentration of glucobrassicin in broccoli was found in the accessions Pirate ( $2.8 \mu\text{mol g}^{-1}$  DW) and Shogun ( $2.4 \mu\text{mol g}^{-1}$  DW), while the lowest concentration was found in Galaxy, Majestic, and MA 191 DH X6 ( $0.3 \mu\text{mol g}^{-1}$  DW). The sums of residual indole glucosinolates (4-hydroxyglucobrassicin, 4-methoxyglucobrassicin, and neoglucobrassicin) were small and relatively similar among the broccoli accessions (Table 2), except in Peto no. 10 which contained a significant amount of 4-hydroxy glucobrassicin ( $3.4 \mu\text{mol g}^{-1}$  DW). In contrast to aliphatic glucosinolates, which are predominately under genetic control (Magrath et al., 1994), the concentration of the indole forms has been proposed to be regulated primarily by environmental and/or physiological factors (Mithen et al., 1995).

In Brussels sprouts, the accession Jersey had nearly 2–3-fold higher aliphatic glucosinolates than the other four accessions (Table 2). The predominant aliphatic glucosinolates in Jersey were gluconapin, sinigrin, and progoitrin at 12.5, 9.1, and  $7.3 \mu\text{mol g}^{-1}$  DW, respectively. Significant differences were also detected in indole glucosinolates content among the five Brussels sprouts accessions (Table 2). The accessions Cambridge no. 5 and Yates Darkcrop have 56 and 69% higher glucobrassicin concentration than the accession Long Island, respectively. Other indole glucosinolates (summed as residual) were relatively similar among the Brussels sprouts accessions (Table 2).

Among cabbage accessions, PI 1214148 had the highest concentration of total aliphatic glucosinolates ( $39.0 \mu\text{mol g}^{-1}$  DW), while Peto no. 27 had the lowest ( $5.6 \mu\text{mol g}^{-1}$  DW) concentration. The predominant aliphatic glucosinolates in PI 1214148 were sinigrin ( $21.1 \mu\text{mol g}^{-1}$  DW), gluconapin ( $13.4 \mu\text{mol g}^{-1}$  DW, included in the residual aliphatic), and progoitrin ( $2.3 \mu\text{mol g}^{-1}$  DW).

Table 2. Glucosinolates Content ( $\mu\text{mol g}^{-1}$  DW) of Individual Accessions within Five *Brassica oleracea* Subspecies

accession	aliphatics					indoles			phenyl
	sinigrin	progoitrin	glucoraphanin	residual	total	glucobrassicin	residual	total	gluconasturtiin
<b>Broccoli</b>									
Atlantic	0.0	0.3	11.6	1.1	12.9	0.7	0.6	1.4	0.5
Baccus	0.0	0.7	1.5	1.2	3.4	0.4	0.7	1.0	0.1
Big Sur	0.0	0.2	2.2	0.6	3.0	0.4	1.0	1.4	0.4
Brigidier	0.0	0.9	21.7	3.8	26.3	1.2	1.0	2.2	0.7
Cavalo Broccolo Ramoso	0.2	1.4	10.2	6.2	18.0	1.8	3.9	5.7	0.8
De Cicco	0.0	0.4	10.7	2.7	13.8	1.7	1.0	2.8	0.6
Eu 4-1	0.0	0.2	7.6	0.4	8.2	0.9	0.6	1.5	0.3
Eu 8-1	0.1	7.9	9.6	3.3	20.9	1.3	1.0	2.3	0.6
EV 2-1	0.0	0.2	1.7	1.1	3.0	1.5	1.3	2.8	0.8
EV 6-1	0.0	0.1	0.8	0.4	1.3	0.6	0.5	1.1	0.2
Florette	0.0	0.3	8.7	1.5	10.4	1.0	0.5	1.6	0.6
Fu 549 DH I.S.	0.0	0.3	3.9	3.9	8.1	0.7	0.3	1.1	0.4
G31824	0.0	0.5	7.1	2.5	10.1	0.5	1.6	2.1	0.8
G31825	0.0	3.9	3.3	4.4	11.6	0.6	0.2	0.8	0.2
Galaxy	0.0	1.0	3.4	0.7	5.1	0.3	0.2	0.5	0.2
GC 1-2	0.0	0.1	5.1	0.5	5.7	0.7	0.8	1.4	0.2
GC 3-2	0.3	2.1	1.6	3.2	7.2	1.3	0.2	1.5	0.2
Gem	0.0	0.0	5.0	1.3	6.4	0.5	0.3	0.7	0.3
Green Comet	0.0	1.4	6.4	1.4	9.2	0.4	0.4	0.9	0.3
Greenbelt	0.0	0.4	8.5	0.9	9.8	1.2	0.7	1.8	0.3
GV 8-1	0.0	2.0	6.6	3.9	12.4	0.7	0.9	1.6	0.3
High Sierra	0.3	2.3	4.5	2.9	9.9	0.8	0.6	1.3	0.3
HS 061 DH I.S.	0.0	0.2	7.2	1.1	8.5	0.8	0.4	1.2	0.3
HS 067 DH I.S.	0.0	0.3	7.4	0.7	8.4	0.8	0.4	1.2	0.3
Legacy	0.0	0.1	5.5	1.9	7.5	0.4	0.4	0.8	0.4
MA 065 DH I.S.	0.0	0.2	6.2	0.6	7.0	1.6	0.7	2.4	0.4
MA 191 DH X6	0.1	0.0	13.8	3.8	17.7	0.3	0.7	1.1	0.4
Majestic	0.0	0.1	16.0	3.0	19.1	0.3	0.4	0.7	0.2
Packman	0.1	0.9	4.2	2.4	7.5	0.1	0.3	0.4	0.1
Persius	0.0	0.5	10.6	0.8	11.9	1.0	0.5	1.6	0.5
Peto no. 3	0.0	0.2	7.1	0.6	7.8	0.5	0.3	0.8	0.1
Peto no. 5	0.0	0.3	8.8	0.9	10.1	1.1	0.5	1.5	0.3
Peto no. 6	0.0	0.0	5.5	1.3	6.8	1.5	0.9	2.3	0.4
Peto no. 7	0.1	7.2	5.9	18.3	31.4	1.2	2.4	3.6	0.6
Peto no. 8	0.0	0.1	5.1	0.5	5.8	0.9	0.5	1.4	0.4
Peto no. 10	0.0	0.4	8.5	1.4	10.3	1.8	4.2	6.0	0.6
Peto no. 11	0.0	0.9	2.6	1.4	4.9	1.0	0.8	1.8	0.2
Peto no. 12	0.1	0.1	3.6	4.3	8.0	0.3	0.5	0.8	0.1
Peto no. 13	0.0	0.3	6.0	1.1	7.4	1.0	0.4	1.4	0.4
Peto no. 14	0.0	0.1	7.6	0.9	8.6	0.7	0.5	1.2	0.2
Peto no. 15	0.0	0.6	2.2	0.9	3.7	0.7	0.3	1.0	0.2
Peto no. 16	0.0	0.2	9.1	1.0	10.2	1.5	0.4	1.9	0.4
Pinnacle	0.1	0.3	8.8	2.2	11.4	1.8	1.9	3.7	0.7
Pirate F1	0.0	0.5	10.7	1.9	13.0	2.8	1.3	4.1	0.6
Premium Crop	0.0	1.1	4.7	2.4	8.2	1.3	0.8	2.1	0.4
Shogun	0.8	2.6	11.9	3.3	18.7	2.4	3.8	6.2	0.9
Su 006 DH I.S.	0.2	0.4	1.5	8.7	10.7	1.8	0.8	2.7	0.4
VI 158 DH I.S.	6.0	5.3	9.4	10.5	31.2	1.3	0.6	1.9	0.5
Wintergarden	0.0	0.5	17.5	0.9	18.9	1.6	0.9	2.5	0.5
Zeus	0.0	0.1	2.9	0.8	3.8	1.1	1.3	2.3	0.3
<b>Brussels Sprouts</b>									
Cambridge no. 5	3.2	1.9	0.6	6.2	11.9	5.6	1.6	7.1	0.6
Jersey	9.1	7.3	1.3	14.1	31.7	3.9	0.8	4.6	0.6
Long Island	4.6	1.1	0.4	5.5	11.5	3.6	1.3	4.9	0.2
Yates Darkcrop	5.1	2.2	1.4	6.1	14.8	6.1	1.8	7.9	0.6
<b>Cabbage</b>									
Jersey Wakfield	6.9	0.6	0.4	2.5	10.5	0.6	1.0	1.5	0.4
Peto no. 22	11.2	0.4	0.3	1.2	13.1	0.6	0.4	1.0	0.4
Peto no. 23	7.1	0.2	0.1	0.1	7.4	0.5	0.5	1.0	0.2
Peto no. 24	7.4	0.2	0.1	0.8	8.5	1.3	1.0	2.3	0.6
Peto no. 27	4.3	0.2	0.1	1.0	5.6	1.3	1.0	2.3	0.2
PI 1214148	21.1	2.3	1.8	13.8	39.0	0.9	0.6	1.5	0.7
<b>Cauliflower</b>									
Feng Shan	9.5	0.3	0.2	0.4	10.3	1.1	1.7	2.8	0.6
Peto no. 17	5.7	0.3	0.4	0.8	7.1	0.3	2.4	2.7	0.2
Snow Crown	12.9	0.3	0.9	0.6	14.6	2.3	3.8	6.1	0.4
<b>Kale</b>									
Vates	7.4	0.5	0.6	1.1	9.5	1.6	0.5	2.2	0.4
Winterborne	13.3	0.7	1.4	1.2	16.6	0.7	0.3	1.0	0.4
LSD 0.01 (all)	3.6	1.4	6.3	0.4	11.0	1.8	1.2	3.0	0.5
LSD 0.01 (broccoli only)	1.0	1.3	7.2	0.1	9.7	1.5	1.1	2.7	0.5

<sup>a</sup> Values represent the mean of three replicates per accession.



Concentrations of indole glucosinolates were relatively similar among the cabbage accessions tested.

In cauliflower, sinigrin concentration varied among accessions (Table 2). The highest concentration of sinigrin was found in Snow Crown ( $12.9 \mu\text{mol g}^{-1}$  DW) while the lowest concentration was found in Peto no. 17 ( $5.7 \mu\text{mol g}^{-1}$  DW). Similarly, Snow Crown showed a significantly higher concentration of indole glucosinolates, especially of glucobrassicin ( $2.3 \mu\text{mol g}^{-1}$  DW) and 4-hydroxy glucobrassicin ( $3.4 \mu\text{mol g}^{-1}$  DW, included in residual indoles), than Peto no. 17 and Feng Shan. Peto no. 17 showed a significantly higher concentration of methoxy glucobrassicin ( $1.8 \mu\text{mol g}^{-1}$  DW) compared to Snow Crown and Feng Shan ( $0.3$  and  $0.7 \mu\text{mol g}^{-1}$  DW, respectively). No major differences in the other indole glucosinolates were observed among the three cauliflower accessions.

In kale, the accession Winterborne had about 2-fold higher total aliphatic glucosinolates content (predominantly sinigrin) than the accession Vates. However, Vates had about 2-fold higher total indole glucosinolates (predominantly glucobrassicin) than Winterborne (Table 2).

In addition to genetic factors, variation in glucosinolate content within the groups of *Brassica* examined in this study may have resulted from differences in dates of harvest. In broccoli, we have found a positive and significant correlation ( $r = 0.52$ ,  $P = 0.004$ ) between glucoraphanin levels and date of harvest. For example, the late maturing accessions Peto no. 5 and Peto no. 10 (maturing 79 and 85 days after transplanting, respectively) contained 8.84 and  $8.50 \mu\text{mol g}^{-1}$  DW glucoraphanin, while the earlier maturing accessions EV6-1 and Peto no. 11 (both maturing at 55 days after transplanting) contained 0.8 and  $2.6 \mu\text{mol g}^{-1}$  DW glucoraphanin, respectively (Table 2). Glucoraphanin levels drop precipitously during the first 10 days of growth from seed (Fahey et al., 1997). Rosa et al. (1996) reported higher glucosinolates in spring than fall harvested cabbage. However, these differences were not linked to variation in growing temperatures (Rosa, 1997). In contrast, in a companion study we have found no correlation between broccoli harvest date and carotenoids, tocopherols, and ascorbate levels (Kurilich et al., 1998).

**Interaction between Glucosinolates and Vitamins.** In a companion study, using the same cruciferous accessions, we have evaluated the levels of the antioxidants  $\alpha$ - and  $\gamma$ -tocopherols,  $\alpha$ - and  $\beta$ -carotenes, and ascorbate (Kurilich et al., 1998). Pearson's correlations between glucosinolates and antioxidants in broccoli showed that there are significant and positive interactions between glucoraphanin and  $\alpha$ -tocopherol ( $r = 0.30$ ,  $P = 0.02$ ). Significant and positive correlations were also found between total aliphatic glucosinolates and  $\gamma$ -tocopherol ( $r = 0.38$ ,  $P = 0.006$ ) and gluconasturtiin and  $\gamma$ -tocopherol ( $r = 0.28$ ,  $P = 0.05$ ). However, there were no significant correlations between indole glucosinolates and any of the antioxidants (Kurilich et al., 1998). Vang et al. (1997) reported that anticarcinogenic properties of dietary fruit and vegetables are likely to be due to a combination of substances acting simultaneously. The significant and positive correlations between glucosinolates and  $\alpha$ - and  $\gamma$ -tocopherol reported in this study indicate added health benefit from consuming crucifer vegetables rich in these compounds.

Variation in glucosinolate levels between and within each group of *Brassica* vegetables suggests differences in their health-promoting properties. Recently, Faulkner et al. (1998) reported 10-fold higher glucoraphanin levels in hybrid lines developed from crosses between wild *Brassica oleracea* and broccoli accessions. When murine hepatoma Hepa 1c1c7 were treated with extracts from the high glucoraphanin lines, they exhibited more than a 100-fold increase in quinone reductase activity over broccoli accessions. Quinone reductase, glutathione *S*-reductase, and UDP-glucuronosyl transferase are phase II detoxification enzymes that have been shown to be induced by a diet rich in crucifer vegetables (Prochaska et al. 1992). These enzymes, through modification of the reactive products of cytochrome P450 oxidation, cause detoxification of carcinogens (Prochaska et al., 1992). Staack et al. (1998) reported that a mixture of glucosinolate breakdown products, similar to that found in a crucifer diet, greatly enhanced the synthesis of detoxification enzymes. They also found that glucosinolates interacted synergistically to induce higher levels of phase II detoxification enzymes and that the induction is dose dependent.

The diversity in glucosinolate levels reported in this and other studies suggests that the potential health benefits from crucifer vegetables are greatly dependent on the accession selected. Previous studies have suggested that enhancing the level of glucosinolates in cruciferous vegetables through conventional breeding or genetic engineering can be expected to enhance the chemopreventive properties of these vegetables. The wide range of variability in glucosinolates among and within the five *Brassica* groups that were evaluated in this study offer an important information base for developing accessions with enhanced health benefits.

#### NOMENCLATURE

Sinigrin, allyl-glucosinolate; gluconapin, butyl-3-enyl-glucosinolate; glucobrassicinapin, pent-4-enyl-glucosinolate; progoitrin, (2*R*)-2-hydroxybut-3-enylglucosinolate; epiprogoitrin, (2*S*)-2-hydroxybut-3-enylglucosinolate; glucoiberin, 3-methylsulfinylpropyl-glucosinolate; glucoraphanin, 4-methylsulfinylbutyl-glucosinolate; glucoalytin, 5-methylsulfinylpentyl-glucosinolate; gluconasturtiin, phenethyl-glucosinolate; glucobrassicin, indol-3-ylmethyl-glucosinolate; neoglucobrassicin, *N*-methoxyindol-3-ylmethyl-glucosinolate; 4-OH glucobrassicin, 4-hydroxyindol-3-ylmethyl-glucosinolate; 4-CH<sub>3</sub>O glucobrassicin, 4-methoxyindol-3-ylmethyl-glucosinolate; sulforaphane, 1-isothiocyanate-4-(methylsulfinyl)-butane.

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#### LITERATURE CITED

- Bones, A. M.; Rossiter, J. The myrosinase-glucosinolate system, its organization and biochemistry. *Physiol. Plant.* **1996**, *97*, 194–208.
- Booth, E. J.; Walker, K. C. A time-course study of the effect of sulphur on glucosinolates in oilseed rape (*Brassica napus*) from the vegetative stage to maturity. *J. Sci. Food Agric.* **1991**, *56*, 479–493.
- Bradfield, C. A.; Bjeldanes, L. F. Effect of dietary indole-3-carbinol on intestinal and hepatic monooxygenase, glutathione *S*-transferase and epoxide hydrolase activities in the rat. *Food Chem. Toxicol.* **1984**, *22*, 977–982.



- Carlson, D. G.; Daxenbichler, M. E.; Tookey, H. L.; Kwolek, W. F.; Hill, C. B.; William, P. H. Glucosinolates in turnip tops and roots: cultivars grown for greens and/or roots. *J. Am. Soc. Hortic. Sci.* **1987a**, *112*, 179–183.
- Carlson, D. G.; Daxenbichler, M. E.; VanEtten, C. H.; Kwolek, W. F.; William, P. H. Glucosinolates in crucifer vegetables: broccoli, brussels sprouts, cauliflower, collard, kale, mustard greens, and kohlrabi. *J. Am. Soc. Hortic. Sci.* **1987b**, *112*, 173–178.
- Chiang, W. C.; Pusateri, D. J.; Leitz, R. E. Gas chromatography/mass spectrometry method for the determination of sulforaphane and sulforaphane nitrile in broccoli. *J. Agric. Food Chem.* **1998**, *49*, 1018–1021.
- Clossais-Besnard, N.; Larher, F. Physiological role of glucosinolates in *Brassica napus*. Concentration and distribution pattern of glucosinolates among plant organs during a complete life cycle. *J. Sci. Food Agric.* **1991**, *56*, 25–38.
- Fahey, J. W.; Zhang, Y.; Talalay, P. Broccoli sprouts: an exceptionally rich source of inducers of enzymes that protect against chemical carcinogens. *Proc. Natl. Acad. Sci. U.S.A.* **1997**, *94*, 10367–10372.
- Farnham, M.; Caniglia, E.; Thomas, C. Utility of DNA flow cytometry for ploidy determination of anther-derived broccoli: effect of leaf age and sampling protocols. *HortScience* **1997**, *32*, 512.
- Faulkner, K.; Mithen, R.; Williamson, G. Selective increase of the potential anticarcinogen 4-methylsulphinylbutyl glucosinolate in broccoli. *Carcinogenesis* **1998**, *19*, 605–609.
- Fenwick, G. R.; Heaney, R. K. Glucosinolates and their breakdown products in cruciferous crops, food, and feeding stuffs. *Food Chem.* **1983**, *11*, 249–271.
- Fenwick, G. R.; Heaney, R. K.; Mullin, W. J. Glucosinolates and their breakdown products in food and food plants. *CRC Crit. Rev. Food Sci. Nutr.* **1983**, *18*, 123–201.
- Fieldsend, J.; Milford, G. Changes in glucosinolates during crop development in single- and double-row genotypes of winter oilseed rape (*Brassica napus*): I. Production and distribution in vegetative tissues and developing pods during development and potential role in the recycling of sulphur within the crop. *Ann. Appl. Biol.* **1994**, *124*, 531–542.
- Foster, R.; Maynard, E. Midwest vegetable production guide for commercial growers. *University of Illinois Coop. Exten. Ser.* **1998**, *C-1356*, 40–44.
- Giamoustaris, A.; Mithen, R. Genetics of aliphatic glucosinolates IV. Side chain modification in *Brassica oleracea*. *Theor. Appl. Genet.* **1996**, *93*, 1006–1010.
- Goodrich, R.; Anderson, J.; Stoewsand, G. Glucosinolate changes in blanched broccoli and Brussels sprouts. *J. Food Process. Preserv.* **1989**, *13*, 275–280.
- Graham, S. Results of case-control studies of diets and cancer in Buffalo, New York. *Cancer Res.* **1983**, *43*, 2409–2413.
- Griffiths, D. W.; Bradshaw, J. E.; Taylor, J.; Gemmell, D. Effect of cultivar and harvest date on the glucosinolate and S-methylcystein sulphoxide content of swedes (*Brassica napus* ssp *rapifera*). *J. Sci. Food Agric.* **1991**, 539–549.
- Guo, Z.; Smith, T.; Wang, E.; Sadrieh, N.; Ma, Q.; Thomas, P.; Yang, C. Effect of phenethyl isothiocyanate, a carcinogenesis inhibitor, on xenobiotic-metabolizing enzymes and nitrosamine metabolism in rats. *Carcinogenesis* **1992**, *13*, 2205–2210.
- Hansen, M.; Moller, P.; Sorensen, H. Glucosinolates in broccoli stored under controlled atmosphere. *J. Am. Soc. Hortic. Sci.* **1995**, *120*, 1069–1074.
- Heaney, R. K.; Fenwick, G. R. The analysis of glucosinolates in *Brassica* species using gas chromatography, direct determination of the thiocyanate ion precursors, glucobrassicin and neoglucobrassicin. *J. Sci. Food Agric.* **1980a**, *31*, 593–599.
- Heaney, R. K.; Fenwick, G. R. Glucosinolates in *Brassica* vegetables. Analysis of 22 varieties of Brussels sprouts (*Brassica oleracea* L. var. *Gemmifera*). *J. Sci. Food Agric.* **1980b**, *31*, 785–793.
- Heaney, R. K.; Fenwick, G. R. Methods for glucosinolate analysis. *Methods Plant Biochem.* **1993**, 531–550.
- Hill, C. B.; Williams, P. H.; Carlson, D. G.; Tookey, H. L. Variation in glucosinolates in oriental brassica vegetables. *J. Am. Soc. Hortic. Sci.* **1987**, *122*, 309–313.
- Jeffery, E.; Wallig, M.; Hudson, A.; Munks, R.; Neal, G.; Judah, D.; Barrett, M.; Clark, H.; Manson, M. Mechanism of action of vegetable constituents in chemoprevention of aflatoxin B<sub>1</sub> hepatocarcinogenesis. *Proc. Am. Assoc. Cancer Res.* **1996**, *37*, 265.
- Josefsson, E. Glucosinolate content and amino acid composition of rapeseed (*Brassica napus*) meal as affected by sulphur and nitrogen nutrition. *J. Sci. Food Agric.* **1970**, *21*, 98–103.
- Kohlmeier, L.; Su, L. Cruciferous vegetable consumption and colorectal cancer risk: meta-analysis of the epidemiological evidence. *FASEB J.* **1997**, *11*, 369.
- Kurilich, A. C.; Tsau, G. J.; Howard, L.; Brown, A.; Klein, B.; Jeffery, E.; Kushad, M.; Wallig, M. Carotenoid, tocopherol, and ascorbate variability in cruciferous vegetables. *Abstracts of Papers*, 95th Annual International Conference of the American Society for Horticultural Science, Salt Lake, UT; American Society for Horticultural Science: Washington, DC, 1998; Vol. 33, p 457.
- Magrath, R.; Morgen, M.; Bano, F.; Parkin, I.; Sharpe, A.; Lister, C.; Turner, J.; Dean, C.; Lydiate, D.; Mithen, R. Genetics of aliphatic glucosinolates I. Side chain elongation in *Brassica napus* and *Arabidopsis thaliana*. *Heredity* **1994**, *72*, 290–299.
- Mithen, R.; Raybould, A.; Giamoustaris, A. Divergent selection for secondary metabolites between wild population of *Brassica oleracea* and its implication for plant-herbivore interaction. *Heredity* **1995**, *75*, 472–484.
- Morse, M. A.; Wang, C. X.; Stoner, G. D.; Mandal, S. G.; Conran, P. B.; Amin, S. G.; Hecht, S. S.; Chung, F. L. Inhibition of 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK)-induced DNA adduct formation and tumorigenicity in lung of F344 rats by dietary phenethylisothiocyanate. *Cancer Res.* **1989**, *49*, 549–553.
- Mullin, W.; Sahasrabudhe, M. Glucosinolates content of cruciferous vegetable crops. *Can. J. Plant Sci.* **1977**, *57*, 1227–1230.
- Nijhoff, W. A.; Grubben, M. J.; Nagengast, F. M.; Jansen, J. B.; Verhagen, H.; Vanpoppel, G.; Peters, W. H. Effects of consumption of Brussels sprouts on intestinal and lymphocytic glutathione S-transferases in humans. *Carcinogenesis* **1995**, *16*, 2125–2128.
- Pocock, K.; Heaney, R. K.; Wilkinson, A.; Beaumont, J. E.; Vaughan, J. G.; Fenwick, G. R. Changes in myrosinase activity and isoenzyme pattern, glucosinolate content and the cytology of myrosinase cells in the leaves of head of three cultivars of English white cabbage. *J. Sci. Food Agric.* **1987**, *41*, 245–257.
- Prochaska, H.; Santamaria, A.; Talalay, P. Rapid detection of inducers of enzymes that protect against carcinogenesis. *Proc. Natl. Acad. Sci. U.S.A.* **1992**, *89*, 2394–2398.
- Ringenberg, M.; Wallig, M. The effect of sulforaphane nitrile (SN) and iberine nitrile (IN) on hepatic glutathione (GSH) concentrations and GSH S-transferase (GST) activity. *Abstract of papers*, Conference on Experimental Biology, Washington, DC; Federation of the American Society for Experimental Biology: Bethesda, MD, 1996; Vol. 10, 3.
- Rosa, E. A. Daily variation in glucosinolate concentrations in the leaves and roots of cabbage seedlings in two constant temperature regimes. *J. Sci. Food Agric.* **1997**, *73*, 364–368.
- Rosa, E. A.; Heaney, R. K.; Portas, C. A.; Roger, G. Changes in glucosinolate concentrations in *Brassica* crops (*B. oleracea* and *B. napus*) throughout growing seasons. *J. Sci. Food Agric.* **1996**, *71*, 237–244.
- Shelp, B. J.; Liu, L.; McLellan, D. Glucosinolate composition of broccoli (*Brassica oleracea* var. *Italica*) grown under various boron treatments at three Ontario sites. *Can. J. Plant Sci.* **1993**, *73*, 885–888.
- Sones, K.; Heaney, R.; Fenwick, G. R. Glucosinolates in *Brassica* vegetables. Analysis of twenty-seven cauliflower cultivars

- (*Brassica oleracea* L. var. *botrytis* subvar. *Cauliflora* DC). *J. Sci. Food Agric.* **1984**, *35*, 762–766.
- Staack, R.; Kingston, S.; Wallig, M.; Jeffery, E. A comparison of the individual and collective effects of four glucosinolate breakdown products from Brussels sprouts on induction of detoxification enzymes. *Toxic. Appl. Pharmacol.* **1998**, *149*, 17–23.
- Tawfiq, N.; Heaney, R. K.; Plumb, J. A.; Fenwick, G. R.; Musk, S. R.; Williamson, G. Dietary glucosinolates as blocking agents against carcinogenesis- Breakdown products assessed by induction of quinone reductase activity in murine hepalc7 cells. *Carcinogenesis* **1995**, *16*, 1191–1194.
- VanEtten, C. H.; Daxenbichler, M. E. Glucosinolates and derived products in cruciferous vegetables. Analysis of the edible part from twenty-two varieties of cabbage. *J. Agric. Food Chem.* **1976**, *24*, 452–455.
- Vang, O.; Rasmussen, B.; Anderson, O. combined effects of complex mixtures of potentially anti-carcinogenic compounds on antioxidant enzymes and carcinogen metabolizing enzymes in the rat. *Cancer Lett.* **1997**, *114*, 283–286.
- Wathlelet, J. P.; Wagstaffe, P. J.; Boeke, A. The certification of the total glucosinolate and sulfur contents of three rapeseeds (colza). *Commission Euro. Commun.* EUR 13339 EN **1991**, 67–70.
- Wattenberg, L. W. Inhibition of carcinogenesis by nonnutrient constituents of the diet. In *Food and Cancer Prevention: Chemical and Biological Aspects*; Waldron, K. W., Johnson, I. T., Eds.; The Royal Society of Chemistry: London, England, 1993; pp 12–24.
- Wattenberg, L. W.; Loub, W. D. Inhibition of polycyclic aromatic hydrocarbon-induced neoplasia by naturally occurring indoles. *Cancer Res.* **1978**, *38*, 1410–1413.
- Zhang, Y.; Talalay, P.; Cho, C.-G.; Posner, G. H. A major inducer of anticarcinogenic protective enzymes from broccoli: isolation and elucidation of structure. *Proc. Natl. Acad. Sci. U.S.A.* **1992**, *89*, 2399–2403.
- Zhang, Y.; Kensler, T. W.; Chao, C.-G.; Posner, G. H.; Talalay, P. Anticarcinogenic activities of sulforaphane and structurally related synthetic norbornyl isothiocyanates. *Proc. Natl. Acad. Sci. U.S.A.* **1994**, *91*, 3147–3150.
- Zhao, F.; Evans, E.; Bilsborrow, P.; Syers J. K. Influence of nitrogen and sulphur on the glucosinolate profile of rapeseed (*Brassica napus* L.). *J. Sci. Food Agric.* **1994**, *64*, 295–304.

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